Gould's Belt,

Interstellar Clouds,

and

the Eocene-Oligocene

Helium-3 Spike

by

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Abstract

Drag from hydrogen in the interstellar cloud which formed Gould's Belt may have sent small meteoroids with embedded helium to the Earth, perhaps explaining part or all of the ^{3}He spike seen in the sedimentary record at the Eocene-Oligocene transition. Assuming the Solar System passed through part of the cloud, meteoroids in the asteroid belt up to centimeter size may have been dragged to the resonances, where their orbital eccentricities were pumped up into Earth-crossing orbits.

1. Introduction

Bekki (2009) has suggested that a blob of dark matter collided with an interstellar cloud ~35 × 10^6 y ago, and that the collision triggered star formation, resulting in the young stars in Gould's Belt. The Solar System is currently near the center of Gould's Belt (also called the Gould Belt). It seems reasonable to suppose that, if Bekki's scenario is correct, the dark matter blob and/or the cloud stirred up comets in the Oort Cloud and sent some into the inner Solar System. Two of these comets may have caused the Chesapeake Bay and Popigai impact structures (e.g., Farley, 2001; Bodiselitsch et al., 2004; Tagle and Claeys, 2004; Fernandez et al. 2014). These or similar impacts may be partly or wholly responsible for the Eocene-Oligocene extinctions. Andrew Brooks wondered if the dark matter blob actually triggered the earlier Cretaceous-Tertiary extinctions   ~65   × 10^6 y   ago,   killing   off   the   dinosaurs (http://staff.unak.is/andy/Presentations/What happened to the Gould Belt.pdf), but this pushes Bekki's blob-cloud collision back by a factor of 2 in time. Bekki's timescale is assumed here.

It also seems reasonable to suppose that the temporary factor of 2 increase in the influx of extraterrestrial ^{3}He seen in the sedimentary record 36 - 34 × 10^6 y ago (Farley 2001; Mukhopadhyay et al. 2001) was caused by the cometary shower. The increase could be from comets shedding dust in the Solar System, or from comet impacts on the Earth. Other mechanisms are comet collisions with asteroids which send matter to Earth, and the two-step process of comets colliding with asteroids, sending meteoroids to the

Moon, with ejecta from the lunar impacts subsequently making their way to Earth (Fritz et al., 2007).

While the passage of a dark matter blob appears to be a plausible explanation for the comet impacts, possibly playing a role in the biological extinctions à la the dinosaurs, as well as the ^{3}He increase, the present paper pursues an alternative idea for the helium spike: instead of a cometary shower, the ^{3}He enhancement may have been due to the Solar System passing through a part of the interstellar cloud which ultimately formed Gould's Belt.

The idea is as follows. Drag from the constituents in the cloud, mainly neutral molecular hydrogen (H_2), affects the orbits of small, up to centimeter-sized meteoroids in the asteroid belt, eventually delivering some of the meteoroids to the resonances and thence to Earth with their load of helium.

The orbit of one such meteoroid is shown in Fig. 1. At A the meteoroid runs into the hydrogen head-on, causing drag. At B the hydrogen instead pushes the meteoroid along. However, what happens at B does not cancel what happens at A: the meteoroid encounters fewer hydrogen molecules and lower speed impacts at B because the relative velocity is smaller there. When averaged over the whole orbit the drag force wins, and the semimajor axis decreases, driving the meteoroid inward toward a resonance.

Many of the tinier meteoroids will reach the resonances during cloud passage because drag is an area-to-mass effect and moves small objects longer distances than large objects. Once these tinier objects reach the resonances, the orbital eccentricities will be rapidly pumped up, bringing them into the inner Solar System (Gladman et al., 1997). Some will fall on our planet. Hence ~35 × 10^6 y ago there will have been something of a

meteorite shower on the Earth. The meteorites will bring in ^{3}He, which ends up in the sediments. Other meteoroids will impact on the lunar surface, with perhaps some of the ejecta reaching the Earth with their own freight of helium (Fritz et al., 2007).

A schematic of the process is shown in Fig. 2. The figure assumes that, before the cloud arrives, meteoroids of all sizes occupy the regions between the resonances, with smaller meteoroids being more numerous than large ones. Once in the cloud, the meteoroids move sunward toward the nearest resonance. How far each moves during cloud passage depends on when it was created, size, shape, composition (which determines density), and original distance from the resonance.

The climatological and biological effects from the Earth's passage through an interstellar cloud has been investigated by several authors (e.g., McKay and Thomas, 1978; Zank and Frisch, 1999; Yaghikyan and Fahr, 2003, 2004a, 2004b; Bodiselitsch et al. 2004; Pavlov et al., 2005). Important as these effects are, the present paper examines only possible drag effects on small Solar meteoroids due to the cloud that formed the Gould Belt. Gravitational interactions with the cloud or the blob are ignored. Smirnova (2004) discusses possible dynamical Solar System consequences from the Gould Belt.

2. Molecular hydrogen drag

This section makes a simple estimate of the amount of molecular hydrogen drag on a meteoroid. In Fig. 3 a spherical meteoroid is in a circular orbit with semimajor axis *a*. The orbit lies in the *x-y* plane with the Sun at the origin. The cloud's hydrogen is assumed to drift through the Solar System from the *y*-direction at an angle θ to the orbit

normal (the *z*-axis), with no solar gravitational bending of trajectories. The concentration is uniform over space. The hydrogen velocity is

$$\mathbf{v_H} = -v_H(\sin\theta\hat{\mathbf{y}} + \cos\theta\hat{\mathbf{z}}) , \tag{1}$$

while that of the meteoroid is

$$\mathbf{v_M} = v_M\hat{\mathbf{t}} = v_M(-\sin\psi\hat{\mathbf{x}} + \cos\psi\hat{\mathbf{y}}) . \tag{2}$$

In the above $v_H = |\mathbf{v_H}|$, $v_M = |\mathbf{v_M}|$, $\hat{\mathbf{x}}$, $\hat{\mathbf{y}}$, and $\hat{\mathbf{z}}$ are the unit vectors along the respective axes, $\hat{\mathbf{t}}$ is the unit along-track vector, while ψ is the angle from the *x*-axis. Also, $\Delta v = |\mathbf{v_M} - \mathbf{v_H}|$ is the relative speed between the meteoroid and the hydrogen.

The mass of hydrogen impacting in 1 s on a 1 m^2 surface which is perpendicular to the relative velocity is $\rho_H \times \Delta v \times 1$ m$^2 \times 1$ s, where ρ_H is the molecular hydrogen density in the cloud. For a spherical meteoroid of mass *M*, radius *R*, and density ρ, the acceleration of the meteoroid from inelastic collisions is

$$\vec{\mathbf{f}} \approx -\frac{\pi R^2 \rho_H \Delta v}{M}(\mathbf{v_M} - \mathbf{v_H}) = -\frac{3\rho_H \Delta v}{4\rho R}(\mathbf{v_M} - \mathbf{v_H}) \tag{3}$$

after using $M = 4\pi\rho R^3/3$. By (1) and (2)

$$(\Delta v)^2 = (\mathbf{v_M} - \mathbf{v_H})\cdot(\mathbf{v_M} - \mathbf{v_H}) = v_M^2 + v_H^2 + 2v_M v_H \sin\theta\cos\psi .$$

Also by (1) and (2)

$$(\mathbf{v_M} - \mathbf{v_H}) \cdot \hat{\mathbf{t}} = v_M + v_H \sin\theta \cos\psi \quad .$$

The meteoroid's along-track acceleration S is $S = \vec{\mathbf{f}} \cdot \hat{\mathbf{t}}$. The along-track acceleration when averaged over the orbit $<S>$ is then by (3)

$$\langle S \rangle = -\frac{3\rho_H}{4\pi\rho R} \int_0^\pi (v_M^2 + v_H^2 + 2v_M v_H \sin\theta\cos\psi)^{1/2}(v_M + v_H \sin\theta\cos\psi)d\psi , \qquad (4)$$

where by symmetry the average of S over $0 \le \psi \le \pi$ is the same as for $\pi \le \psi \le 2\pi$. Switching the variable to $\lambda = \psi/2$ gives $\cos\psi = \cos^2\lambda - \sin^2\lambda = 1 - 2\sin^2\lambda$, resulting in

$$(v_M{}^2 + v_H{}^2 + 2v_M v_H \sin\theta\cos\psi)^{1/2} = 2v_M[(v_H/v_M)\sin\theta]^{1/2}H/k$$

where $H = (1 - k^2\sin^2\lambda)^{1/2}$, and

$$k^2 = 4(v_H/v_M)\sin\theta/[1 + (v_H/v_M)^2 + 2(v_H/v_M)\sin\theta] \quad .$$

Thus (4) becomes

$$\langle S \rangle = -\frac{3\rho_H v_M^2}{2\pi\rho R}\left[\left(\frac{v_H}{v_M}\right)\left(\frac{\sin\theta}{k^2}\right)\right]^{1/2}$$

$$\cdot \left\{ [1 + (v_H / v_M) \sin\theta] \int_0^{\pi/2} H \, d\lambda - 2(v_H / v_M) \sin\theta \int_0^{\pi/2} H \sin^2 \lambda \, d\lambda \right\} \quad . \tag{5}$$

Now

$$\int_0^{\eta} H \, d\lambda = E(\eta, k)$$

and

$$\int_0^{\eta} H \sin^2 \lambda \, d\lambda = -\left(\frac{1}{3}\right) H \sin\eta \cos\eta + \left(\frac{2k^2 - 1}{3k^2}\right) E(\eta, k) + \left(\frac{1 - k^2}{3k^2}\right) F(\eta, k)$$

(Gradshteyn and Ryzhik, 1980, p. 158). Here $E(\eta, k)$ and $F(\eta, k)$ are the usual elliptic integrals

$$E(\eta, k) = \int_0^{\eta} \left(1 - k^2 \sin^2 \lambda\right)^{1/2} d\lambda$$

and

$$F(\eta, k) = \int_0^{\eta} \frac{1}{\left(1 - k^2 \sin^2 \lambda\right)^{1/2}} d\lambda \quad .$$

Thus

$$\langle S \rangle = -\frac{3\rho_H v_M^2}{4\pi\rho R}\left[1+\left(\frac{v_H}{v_M}\right)^2+2\left(\frac{v_H}{v_M}\right)\sin\theta\right]^{1/2}\left\{E+\frac{1}{3}\left(\frac{v_H}{v_M}\right)\sin\theta\left[\left(\frac{2}{k^2}-1\right)E+2\left(1-\frac{1}{k^2}\right)F\right]\right\} \quad (6)$$

where $E = E(\pi/2, k)$ and $F = F(\pi/2, k)$. The values of $E(\pi/2, k)$ and $F(\pi/2, k)$ can be found

from tables for given values of k, such as listed in Selby (1974, pp. 551-553).

The estimated range of values for $\langle S \rangle$ as a function of θ and v_H/v_M will be taken

up next. The estimated lower bound on $\langle S \rangle$ will be found first. Evaluating it for $\theta = 0$

gives $k = 0$ and $E(\pi/2, 0) = F(\pi/2, 0) = \pi/2$. Hence (6) becomes

$$\langle S \rangle = -\frac{3\rho_H}{8\rho R}(v_M^2 + v_H^2)^{1/2} v_M \quad . \tag{7}$$

This expression gives the smallest value for $\langle S \rangle$ as a function of θ.

An estimate for the smallest value as a function of v_H/v_M can be found by

assuming the motion of the Sun relative to the cloud is infinitesimal, so that v_H is entirely

due to the hydrogen falling from infinity with zero velocity. Therefore the value of v_H is

approximately the escape velocity for the chosen value of orbital semimajor axis a of the

meteoroid, giving

$$v_M = (GM_S/a)^{1/2} \tag{8}$$

and

$$v_H = (2GM_S/a)^{1/2} \ , \tag{9}$$

where $G = 6.6726 \times 10^{-11}$ kg^{-1} m^3 s^{-2} is the universal constant of gravitation and $M_S = 1.989 \times 10^{30}$ kg is the Sun's mass. Thus $v_H/v_M = 2^{1/2}$. For example, $v_M = 17.196$ km s^{-1} and $v_H = 24.319$ km s^{-1} for $a = 3$ AU.

Plugging (8) and (9) into (7) yields

$$\langle S \rangle_{min} = -\frac{3^{3/2} \rho_H}{8 \rho R} \left(\frac{GM_S}{a} \right) \ . \tag{10}$$

This is the estimated minimum value as a function of both θ and v_H/v_M and is the left-most value of the top curve in Fig. 4. The rest of the top curve is found by varying θ in (6). The value of $<S>$ is only very weakly dependent on θ for $v_H/v_M = 2^{1/2}$.

A very generous estimated upper bound $<S>_{max}$ is found by simply assuming that v_H is a high 100 km s^{-1}. (The speed is high because a drift speed of 75 km s^{-1} would carry the Solar System 150 pc through the cloud in 2×10^6 y.) In this case $v_H/v_M = 5.8153$ at $a = 3$ AU. The result is the bottom curve in Fig. 4 after once again using (6). Here the difference between the largest value ($\theta = \pi/2$) and the smallest value ($\theta = 0$) is only a factor of ~1.5. Also, the maximum difference between the top and bottom curves is only a factor of ~5. Given that the upper bound $<S>_{max}$ is quite generous, it is unlikely that $<S>$

departs by more than a factor of ~2 from $<S>_{min}$; hence the value for $<S>_{min}$ is used in what follows. The greatest determinant of drag is expected to be the value of ρ_H.

3. Delivery of ^{3}He to Earth

For circular orbits

$$\frac{da}{dt} = \frac{2\langle S \rangle_{min}}{n} \qquad (11)$$

(e.g. Blanco and McCuskey, 1961), where t is time and $n = (GM_S/a^3)^{1/2}$ is the mean motion. Plugging (10) into (11) results in the simple expression

$$\frac{da}{dt} = -\frac{(27GM_S a)^{1/2} \rho_H}{4\rho R} = -\frac{(27GM_S a)^{1/2} m_H N_H}{2\rho R} \quad . \qquad (12)$$

where $\rho_H = 2m_H N_H$, with $m_H = 1.673 \times 10^{-27}$ kg being the mass of the hydrogen atom and N_H being the number of H_2 molecules in a cubic meter. Here it is assumed that $\rho = 2800$ kg m^{-3} for a stony meteoroid and 7870 kg m^{-3} for an iron meteoroid. According to (12), after a time T in the cloud the semimajor axis will have shrunk by an amount Δa, so that (12) can be rewritten

$$R \approx \frac{(27GM_S a)^{1/2} m_H N_H}{2\rho \Delta a} T \quad . \qquad (13)$$

The shower intensity is taken to be a "boxcar" function in time, so that it abruptly turns on 36×10^6 y ago, remains constant for 2×10^6 y, and just as abruptly turns off at 34×10^6 y ago. For $a = 3$ AU and $T = 2 \times 10^6$ y, (13) yields $R = 5.1 \times 10^{-12} \, N_H/\Delta a$ for stones and $R = 1.8 \times 10^{-12} \, N_H/\Delta a$ for irons, where R is in meters and Δa is in AUs.

Bekki (2009) assumes a huge initial cloud 200 pc in radius, with a mass 10^6 times that of the Sun. This means an initial density of 2×10^{-21} kg m^{-3} before its collapse into star-making. The hydrogen number density N_H in molecular clouds is generally $\sim 10^8$ - 10^9 m^{-3}, while for the denser parts of clouds it can reach as high as $\sim 10^{10}$ - 10^{12} m^{-3} (e.g., Ferrière, 2001, p. 1037). A mid-range value of $N_H = 5 \times 10^8$ m^{-3} for the dilute part of the cloud is assumed here, giving a molecular hydrogen density of $\rho_H = 1.7 \times 10^{-18}$ kg m^{-3}. This shrinks the radius of Bekki's cloud by a factor of ~ 10, which is in line with the size of typical interstellar clouds (e.g., Ferrière, 2001, p. 1037). Using this higher value of 1.7×10^{-18} kg m^{-3} for ρ_H, (13) becomes

$$R \approx 0.0025/\Delta a \tag{14}$$

for stones and

$$R \approx 0.00088/\Delta a \tag{15}$$

for irons, where once again R is in meters and Δa is in AUs.

If the resonances are spaced $\Delta a = $ ~0.1 AU apart in the asteroid belt (e.g.,

Nesvorný et al., 2002), then by (14) and (15) the belt will be swept mostly clean of stony

meteoroids with $R \leq$ ~0.025 m (~2.5 cm) and iron ones with $R \leq$ ~0.0088 m (~1 cm) over

the ~2×10^6 y that the Solar System spends in the cloud. Some larger objects will also

make it to the resonances if they have shorter distances to travel. Many of the meteoroids

which do make it and not skip over the resonances (Bottke et al., 2000) will have their

orbital eccentricities increased until they collide with something or get ejected from the

Solar System. The timescale for pumping up the eccentricities is only ~10^5 - 10^7 y

(Gladman et al., 1997).

Some objects will collide with the Earth; thus a meteoroid shower is an expected

consequence of cloud passage. Because they hold ^{3}He, their fall may be at least partly

responsible for the observed ^{3}He spike seen in the sedimentary record. The rest of the

helium may have arrived in a two-step process where meteoroids also barrage the Moon

and throw out ejecta, which end up on Earth with their own load of ^{3}He (Fritz et al.,

2007).

A crude estimate can be made of the amount of matter collected by the Earth

during the meteoroid shower. Judging from Divine (1993, Fig. 10), the current total

amount of asteroidal material whose particles are < 0.001 kg in mass is roughly 3×10^{15}

kg. Spreading this out evenly in a disk 3 AU in radius and 0.1 AU in thickness gives a

mass density of ~3×10^{-19} kg m^{-3}. The Earth plowing its way through this material would

collect ~$\pi R_E^2 v_E \times (3 \times 10^{-19}) = 1.15$ kg s^{-1} ignoring gravitational focusing, where $R_E = $

6.371×10^6 m is the radius of the Earth and $v_E = 30\ 000$ m s^{-1} is its speed in its orbit. This

amounts to 36 000 tons per year. This is about the same amount of dust collected in one

year by the Earth today (Love and Brownlee, 1993) and about the size of the spike. Meteoroids larger than 0.001 kg will only add to the total. Thus the meteorite shower appears to be a possible explanation for at least part of the ^{3}He spike seen at the Eocene-Oligocene transition.

4. Discussion

The most conservative assumptions were made here to make drag as small as possible, except for the H_2 number density, which took a mid-range value of $N_H = 500 \times 10^6$ m^{-3}. The angle θ is unknown, assuming cloud passage ever happened. The smallest amount of drag as a function of θ occurs when $\theta = 0$, so this value was assumed here. Further, the collision of a meteoroid with the hydrogen was taken to be completely inelastic, which also minimizes drag. Moreover, the drift velocity between the cloud and the Solar System was assumed to be small. Penetration of the hydrogen into the inner Solar System is not expected to be a problem (Yaghikyan and Fahr, 2004b, pp. 1114-1115).

Interstellar clouds are typically tens of light-years in diameter (e.g., Ferrière, 2001, p. 1037). A part of the cloud twenty light-years across which takes two million years to drift through the Solar System implies a low drift speed of 3 km s^{-1}. Much faster speeds would imply a larger cloud if the time stays at 2×10^6 y in the cloud. Faster speeds of course imply more drag by increasing v_H (Fig. 4).

While it was assumed above that the time the Solar System spent in the cloud was the same length of time as the ^{3}He enhancement (2×10^6 y), this may not necessarily be

the case. The Solar System may have swiftly passed through a portion of the cloud, causing high drag for a brief time. In any case, small meteoroids may have been delivered to the resonances which put them into high eccentricity orbits on the 10^5 - 10^7 year timescale (Gladman et al., 1997), which is somewhat consonant with the ^{3}He spike.

Small meteoroids on highly eccentric orbits with apoapses in the asteroid belt might cause collisions which would act like drag and send larger meteoroids to the resonances. These would get their orbital eccentricities pumped up and collide with still larger meteoroids, and so on, causing a cascade over some interval of time, possibly culminating in km-sized asteroids colliding with each other and the Earth. Whether the meteoroids could remain in highly elliptical orbits long enough to cause a cascade and the timescale over which the cascade happens will not be pursued here, though it seems reasonable to assume that it would be many times the Gladman et al. (1997) timescale. The cascade scenario does lead to an interesting question: are we in the midst of a cascade beyond what would normally be expected if the Solar System never passed through an interstellar cloud?

Collisions of meteoroids in the asteroid belt with smaller ones on highly elliptical orbits would also increase space erosion (e.g., Rubincam, 2015). But the erosion would only be expected to erode away only a centimeter on two of a stony meteoroid, and a negligible amount on an iron meteoroid (details omitted).

Interstellar clouds also contain dust which could both drag and erode meteoroids. However, the dust content of a cloud is small compared to the hydrogen (e.g., Ferrière, 2001, Table 1) and is ignored here.

A meteoroid shower seems plausible enough, given the uncertainties, to explain at least part of the factor of 2 spike in the ^{3}He, but bears further investigation. A problem with small meteoroids from the asteroid belt delivering ^{3}He to Earth is their high velocities; the heating from the Earth's atmosphere would cause them to lose much of their helium (Farley 2001; Mukhopadhyay et al. 2001).

This leads to the question as to whether emptying the asteroid belt of meteoroids up to 0.01 m in size would produce enough objects to make up for the high velocities and so explain the helium spike. Further, the hail of meteoroids on the Moon would produce ejecta from the impacts; however, centimeter-sized impactors probably mean that little ejecta would achieve escape velocity and end up on the Earth in the two-step process of Fritz et al. (2007), unless there is something of a collision cascade as mentioned above and relatively large meteoroids strike the Moon. On the other hand, by (13) the meteoroid radius R is linearly dependent on the hydrogen number density N_H. The Solar System may have passed through a much denser part of the cloud than the 5×10^8 kg m^{-3} assumed here, perhaps leading to meteoroids an order-of-magnitude or larger than a centimeter pelting the Earth and Moon.

The effect of the meteoroid barrage on the Earth's biosphere is not clear and may be minimal. Though perhaps of interest, this is not examined here; only the delivery of ^{3}He to Earth is considered in this paper.

Acknowledgments

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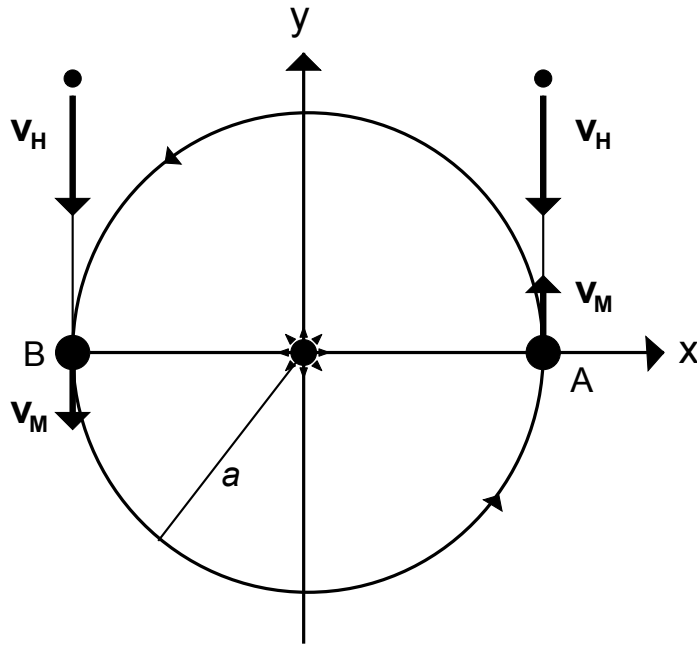   Nine. AIP Conf. Proc. 471, pp. 831-834.

Figures

Fig. 1 Schematic illustrating the drag force on a meteoroid from the interstellar cloud's molecular hydrogen. The meteoroid is in a circular orbit about the Sun with semimajor axis a with velocity $\mathbf{v_M}$. In this diagram the hydrogen molecules (small black dots) lie in the x-y plane and have velocity $\mathbf{v_H}$. The collisions are head-on at A, causing drag on the meteoroid (large black dot). The collisions at B do the opposite, giving the meteoroid a boost. But at B the meteoroid encounters fewer molecules and lower speeds than at A because the relative velocity between the meteoroid and the hydrogen is smaller at B than at A. As a result, there is a net drag and the orbit shrinks.
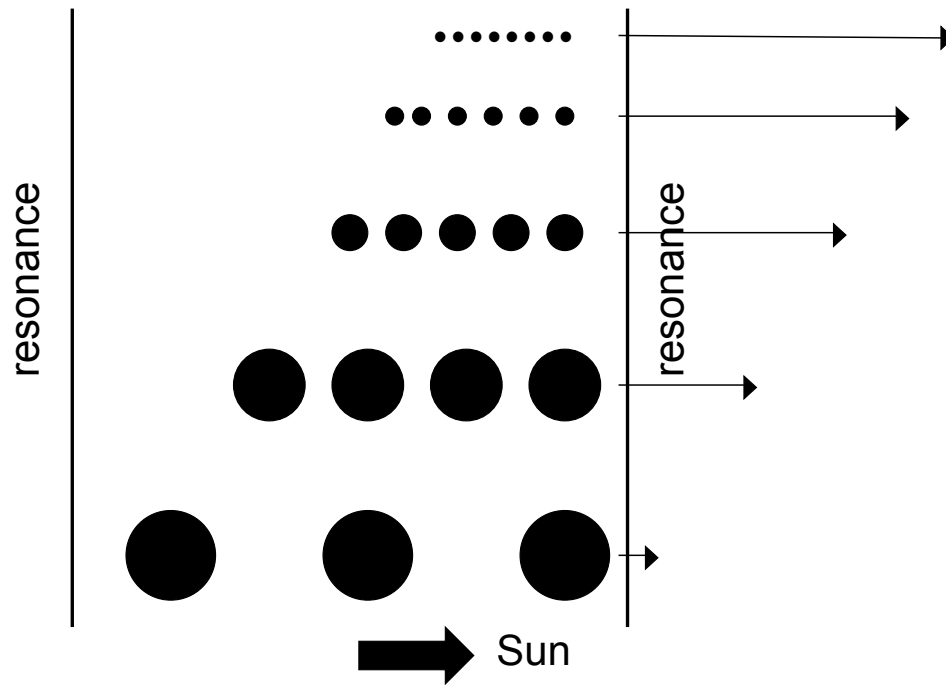
Fig. 2. Schematic of meteoroids which have moved toward the sunward resonance due to the hydrogen drag. Many of the numerous smaller meteoroids (top) pass through the resonance, depleting their number. The larger, less numerous meteoroids (bottom) move only a little, with few reaching the resonance.
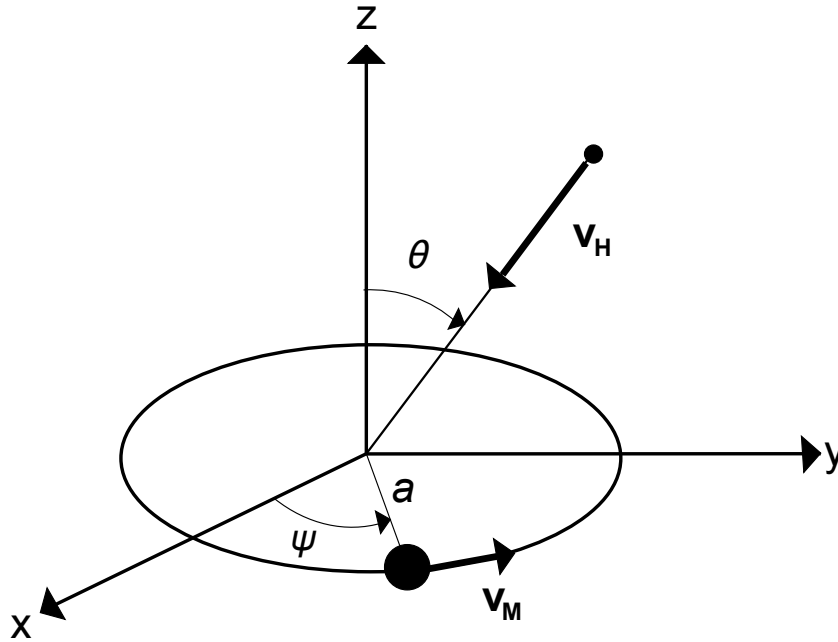
Fig. 3. Geometry of the meteoroid orbit and hydrogen trajectories. The orbit lies in the *x-y* plane and has semimajor axis *a*. The orbit normal is the *z*-axis. The meteoroid (large black dot) has velocity $\mathbf{v_M}$. The position in its orbit makes an angle ψ with the *x*-axis. A hydrogen molecule (small black dot) travels with velocity $\mathbf{v_H}$, with its trajectory lying in the *y-z* plane. The trajectory makes an angle θ with the *z*-axis as shown. All the hydrogen molecules are assumed to be spread uniformly throughout space and have the same velocity and parallel trajectories.
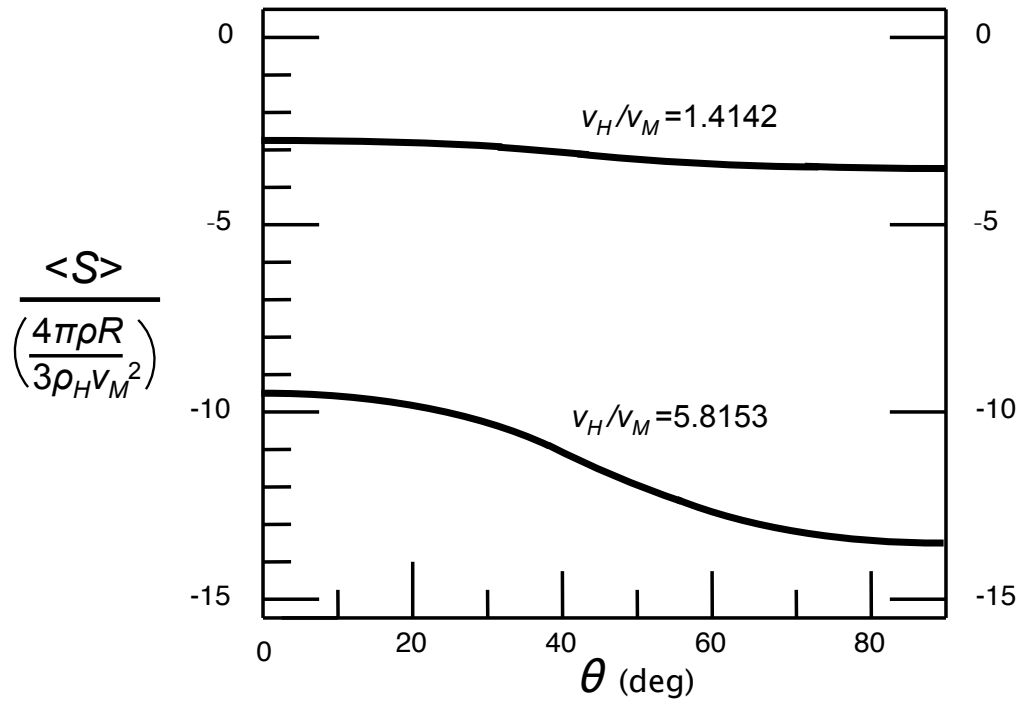
Fig. 4. Behavior of the average along-track acceleration *<S>* of a meteoroid as a function of θ for the maximum and minimum values of v_H/v_M assumed here. The drag becomes greater the closer the hydrogen trajectories come to lying in the meteoroid's orbital plane $(\theta = 90°)$.